American Journal of Epidemiology Volume 163, Number 1 Pp. 27-37

**American Journal of Epidemiology Advance Access originally published online on November 23, 2005**
American Journal of Epidemiology 2006 163(1):27-37; doi:10.1093/aje/kwj001

# Exposure-Effect Relations between Aircraft and Road Traffic Noise Exposure at School and Reading Comprehension

## The RANCH Project

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*Received for publication March 24, 2005. Accepted for publication July 8, 2005.*

## ABSTRACT

Transport noise is an increasingly prominent feature of the urban environment, making noise pollution an important environmental public health issue. This paper reports on the 2001–2003 RANCH project, the first cross-national epidemiologic study known to examine exposure-effect relations between aircraft and road traffic noise exposure and reading comprehension. Participants were 2,010 children aged 9–10 years from 89 schools around Amsterdam Schiphol, Madrid Barajas, and London Heathrow airports. Data from the Netherlands, Spain, and the United Kingdom were pooled and analyzed using multilevel modeling. Aircraft noise exposure at school was linearly associated with impaired reading comprehension; the association was maintained after adjustment for socioeconomic variables (ß = –0.008, $p$ = 0.012), aircraft noise annoyance, and other cognitive abilities (episodic memory, working memory, and sustained attention). Aircraft noise exposure at home was highly correlated with aircraft noise exposure at school and demonstrated a similar linear association with impaired reading comprehension. Road traffic noise exposure at school was not associated with reading comprehension in either the absence or the presence of aircraft noise (ß = 0.003, $p$ = 0.509; ß = 0.002, $p$ = 0.540, respectively). Findings were consistent across the three countries, which varied with respect to a range of socioeconomic and environmental variables, thus offering robust evidence of a direct exposure-effect relation between aircraft noise and reading comprehension.

child psychology; cognition; environment and public health; environmental exposure; noise; reading

Abbreviations: dB(A), a measure of sound level in decibels A-weighted to approximate the typical sensitivity of the human ear

## INTRODUCTION

Exposure to transport noise is an increasing and prominent feature of the urban environment. The ubiquitous demand for air and road travel means that more people are being exposed to transport noise, making noise pollution an increasingly important environmental issue for public health. The effect of chronic aircraft noise exposure and road traffic noise exposure on reading comprehension in primary school children is established (1–6), but, to our knowledge, no exposure-effect relations for aircraft noise or road traffic noise and reading comprehension at the individual level have been established. This paper reports findings of the RANCH project (Road traffic and Aircraft Noise Exposure and Children's Cognition and Health), the largest known epidemiologic study undertaken of noise exposure and children's cognition and health (7), which examined exposure-effect relations between noise exposure at school and reading comprehension in the Netherlands, Spain, and the United Kingdom.

Most previous studies compared the performance of children exposed to high noise levels with children exposed to low noise levels. While demonstrating an effect of chronic noise exposure on reading, these studies provide limited information in terms of the levels at which the effects of noise on children's reading comprehension begin. Previous studies that examined exposure-effect relations between aircraft noise exposure and reading assessed reading retrospectively from school records (8, 9) and may have confounded chronic noise exposure with acute noise exposure during testing. The RANCH project examined children from schools subjected to a wide range of noise exposures, making it possible to establish exposure-effect curves for aircraft and road traffic noise to examine the lowest observable effect level of noise on reading comprehension.

To our knowledge, this study is the first to be able to make intercountry comparisons of the effect size of aircraft and road traffic noise on reading comprehension. Using the same methodology in each country enabled a large sample size to be achieved by pooling the data from each country and comparing the effect size across countries.

Areas with high levels of environmental noise are often socially deprived, and children from areas of high social deprivation perform poorly on reading comprehension tasks, leading to potential confounding (10). Some studies have demonstrated an effect of environmental noise after adjusting for the influence of socioeconomic status (1), and other studies have not (4–6, 8, 10, 11). However, longitudinal studies (12, 13) have found that a reduction in noise exposure eliminated previously observed noise-related reading deficits, suggesting that socioeconomic status does not confound the relation. This study collected comparable data on socioeconomic status in the Netherlands, Spain, and the United Kingdom to examine whether socioeconomic status confounds the relation between chronic noise exposure and reading comprehension.

The relation between noise exposure and reading comprehension may be mediated by other cognitive abilities important in the development of children's reading ability, such as attention, episodic memory, and working memory. While environmental stressors can have a strong impact on the degree to which information is processed, retained, and recalled (14), a previous study found that attention did not mediate the relation between aircraft noise and reading comprehension (1, 11). The current study collected data on attention, episodic memory, and working memory, using the same nonverbal tests in each country, to examine whether these were intervening factors in the relation between noise exposure and reading comprehension.

The aim of this study was to assess exposure-effect relations of chronic aircraft and road traffic noise with reading comprehension, using data from nationally standardized reading comprehension tasks completed by children aged 9–10 years attending schools exposed to a range of aircraft noise and road traffic noise. It was hypothesized that there would be a linear exposure-effect relation between aircraft and road traffic noise at school and reading comprehension: children exposed to high levels of noise would have poorer reading comprehension than children exposed to low levels of noise, after adjustment for socioeconomic factors. The same relation was hypothesized for aircraft noise exposure at home.

## MATERIALS AND METHODS

### Sampling and design

Children were selected to take part in this cross-sectional epidemiologic field study on the basis of levels of noise exposure in schools around major airports in three European countries (Schiphol in Amsterdam, the Netherlands; Barajas in Madrid, Spain; and Heathrow in London, United Kingdom). In each country, primary schools around the airport were identified. In Spain and the United Kingdom, all nonstate schools were excluded, which was not possible in the Netherlands. Within each country, schools were matched according to socioeconomic status. In the Netherlands, a neighborhood-level indicator of property value and the percentage of non-Europeans were used to match schools. In Spain and the United Kingdom, schools were matched according to the percentage of children receiving free school meals and speaking the main language at home. Main language spoken at home reflects the number of children who are bilingual—who are taught in English or Spanish and who speak another language at home, for example, Gujerati in the United Kingdom. Children who were recent immigrants and who did not speak the main language of the country proficiently were excluded from the analysis according to a consistent protocol across all countries.

The schools were visited and a noise survey undertaken. Schools were classified in terms of noise exposure on a 4-by-4 grid ranging ordinally from low to high for aircraft noise and low to high for road traffic noise. In each country, two schools were then selected in each of the noise exposure grid cells, and, within schools, mixed-ability classes of boys and girls aged 9–10 years were selected to take part. No children were excluded from the selected classes.

### Noise exposure assessment

In all three countries, aircraft noise estimates were based on 16-hour outdoor LAeq contours (LAeq is the "equivalent" average sound level measured by using the A-weighting most sensitive to speech intelligibility frequencies of the human ear), which gave the average continuous equivalent sound level of aircraft noise in an area from 7 a.m. to 11 p.m. for a specified period. The aircraft noise contour data were available nationally and were not derived specifically for this study. In Spain and the United Kingdom, the contours available were from July to September for the years 1999 and 2000, respectively; in the Netherlands, the contours were from October 1999 to November 2000. These contours were used to estimate aircraft noise exposure at school and home for each participant. In the Netherlands, estimates of outdoor road traffic noise were provided by modeled data (15✦). In the United Kingdom and Spain, estimates of road traffic noise at school were based on a combination of modeling the proximity to motorways, major roads, and minor roads; traffic flow data; and noise measurements taken at the façade of the school building. In all countries, acute noise measurements were taken both inside and outside the classroom during testing. In all analyses, chronic aircraft and road traffic noise were entered as continuous variables in dB(A); dB(A) is a measure of sound level in decibels A-weighted to approximate the typical sensitivity of the human ear.

### Outcome and confounding factors assessment

#### Reading comprehension measures.

Reading comprehension was measured by using established, nationally standardized tests. In the United Kingdom, the 86-item Suffolk Reading Scale, level 2 was used, which is suitable for children aged 8 years to 11 years, 11 months (16✦). In the Netherlands, the 42-item CITO Readability Index for Elementary and Special Education was used (17✦). This test is designed for children aged 8–12 years. In Spain, the 27-item ECL-2 (Evaluación Comprensión Lectora) was used (18✦). This test is suitable for children aged 8–13 years. *z* scores were computed, which enabled comparisons to be made between each country's test.

#### Potential confounding factors.

Comparable measures of potential confounding factors were achieved across countries by using a questionnaire completed by the child during testing and a parent-completed questionnaire. The questionnaires assessed socioeconomic status, parental and child health, and noise-related annoyance. Owing to the large number of potential confounders, variables were retained in the multivariate analysis if analysis of covariance showed a significant relation between the confounder and aircraft noise exposure and/or road traffic noise exposure ($p < 0.05$) (table 1). The confounders retained in the analysis were age, collected from both school records and parents; employment status: whether the parent worked full or part-time; crowding: the number of people per room in the house, defined as more than 1.5 per room in the United Kingdom and Spain and equal to or more than one per room in the Netherlands (the different cutoff points reflect the different official definitions of this concept in each country); home ownership: whether the home was rented or owned/mortgaged; long-standing illness, based on parental reports of the child having attention deficit hyperactivity disorder, asthma/bronchitis, eczema, epilepsy, depression, diabetes, or dyslexia; main language spoken at home, which indicated whether the child spoke the predominant language for the country at home: Dutch, Spanish, or English; classroom glazing, a measure of the glazing (single, double, or triple) of the windows in the child's classroom; mother's educational attainment, measured by using a relative inequality index based on a ranked index of standard qualifications in each country (19); and parental support for schoolwork, assessed by a self-report scale completed by the child.

**TABLE 1. School- and pupil-level characteristics[*] of the RANCH sample, overall and by country, the RANCH project, 2001–2003[†]**

| Characteristic | Pooled sample | United Kingdom | The Netherlands | Spain |
|---|---|---|---|---|
| | | *School-level data* | | |
| No. of schools | 89 | 29 | 33 | 27 |
| No. of classes | 129 | 47 | 34 | 48 |
| No. of pupils invited | 3,207 | 1,355 | 824 | 1,028 |
| No. of pupils participating | 2,844 | 1,174 | 762 | 908 |
| No. of pupils and parents participating | 2,276 | 960 | 658 | 658 |
| Aircraft noise exposure at school (dB(A)[‡]) | | | | |
| Mean (SD[‡]) | 52 (9.7) | 52 (9.4) | 54 (7.0) | 43 (10.7) |
| Range | 30–77 | 34–68 | 41–68 | 30–77 |
| Road traffic noise exposure at school (dB(A)) | | | | |
| Mean (SD) | 51 (7.57) | 48 (7.25) | 53 (8.87) | 53 (5.98) |
| Range | 32–71 | 37–67 | 32–66 | 43–71 |
| Classroom glazing (%) | | | | |
| Single glazing | 56.2 | 58.6 | 45.5 | 66.7 |
| Double glazing | 39.3 | 41.4 | 42.2 | 33.3 |
| Triple glazing | 4.5 | 0.0 | 12.1 | 0.0 |
| | | *Pupil-level data* | | |
| No. of pupils | 2,844 | 1,174 | 762 | 908 |

| | | | | |
|---|---|---|---|---|
| Response rate (%) | | | | |
| Child | 89 | 87 | 92 | 88 |
| Parent | 80 | 82 | 86 | 72 |
| Aircraft noise exposure at home (dB(A)) | | | | |
| Mean (SD) | 50 (8.9) | 53 (8.9) | 49 (7.06) | 46 (9.1) |
| Range | 31–76 | 33–76 | 34–65 | 31–73 |
| Age | | | | |
| Mean | 10 years, 6 months | 10 years, 3 months | 10 years, 5 months | 10 years, 11 months |
| Range | 8 years, 10 months–12 years, 10 months | 8 years, 10 months–11 years, 11 months | 8 years, 10 months–12 years, 10 months | 9 years, 5 months–12 years, 4 months |
| Gender (%) | | | | |
| Male | 47.1 | 45.1 | 49.9 | 47.1 |
| Female | 52.9 | 54.9 | 50.1 | 52.9 |
| Parents' employment status (%) | | | | |
| Not employed | 14.9 | 22.7 | 7.4 | 11.1 |
| Employed | 85.1 | 77.3 | 92.6 | 88.9 |
| Crowding at home (%) | | | | |
| Not crowded | 78.6 | 77.3 | 68.8 | 90.5 |
| Crowded | 21.4 | 22.7 | 31.2 | 9.5 |
| Parents' home ownership (%) | | | | |
| Not owned | 27.7 | 42.1 | 18.9 | 15.4 |
| Owned | 72.3 | 57.9 | 81.1 | 84.6 |
| Long-standing illness (%) | | | | |
| No | 75.9 | 73.6 | 73.2 | 81.8 |
| Yes | 24.1 | 26.4 | 26.8 | 18.2 |
| Main language spoken at home (%) | | | | |
| No | 11.9 | 22.0 | 6.6 | 2.4 |
| Yes | 88.1 | 78.0 | 93.4 | 97.6 |
| Mother's education[§] (mean (SD)) | 0.50 (0.28) | 0.50 (0.28) | 0.50 (0.28) | 0.50 (0.28) |
| Parental support scale | | | | |

| | | | | |
|---|---|---|---|---|
| Mean (SD) | 10.1 (2.0) | 10.1 (1.9) | 8.8 (1.9) | 11.1 (1.5) |
| Cronbach's $\alpha$ | 0.650 | 0.591 | 0.582 | 0.570 |

* Refer to the Materials and Methods section of the text for a description of the characteristics.

† Some missing values were excluded: age, 5%; gender, <1%; crowding, 7%; home ownership, 6%; long-standing illness, 4%; main language spoken at home, 5%; classroom glazing, 0%; mother's education, 7%; and parental support, 6%.

‡ dB(A), a measure of sound level in decibels A-weighted to approximate the typical sensitivity of the human ear; SD, standard deviation.

§ Measured by using a relative inequality index based on a ranked index of standard qualifications in each country (19); a high score equals lower educational attainment.

**Mediating cognitive factors.**
In all three countries, the same established nonverbal tests of cognition were examined (7). Standardized tests were selected, after pilot studies were conducted in each country, that could be group administered, were valid for the population being assessed in terms of age and learning range, and were suitable for children who did not speak the main language at home. Episodic memory (recognition, information recall, and conceptual recall) was measured by using a task from the Child Memory Scale (20) adapted for group administration. Sustained attention was assessed by using the Toulouse Pieron Test adapted for classroom use (21). Working memory was assessed by using a modified version of the Search and Memory Task (22, 23).

**Procedure**
Group testing was carried out in the classroom, and the cognitive tests were administered as part of a 2-hour testing session conducted in the morning. Written consent was obtained from both parents and the children. Ethical approval was obtained in each country.

**Analysis**
Data from all countries were pooled and analyzed by using MLwiN multilevel modeling software (24), which took into account the hierarchical nature of the data, with pupils being clustered in schools. Statistical significance was tested by comparing the goodness of fit of different models using a chi-square test of deviance.

Analyses of aircraft noise exposure at school and road traffic noise exposure at school were conducted separately to examine single-exposure effects. For each noise exposure type, two models were run: model 1 (unadjusted) contained only noise exposure (either aircraft or road traffic noise at school); model 2 included both noise exposures and was adjusted for age, gender, country, mother's educational attainment, parental employment status, crowding in the home, parental home ownership, long-standing illness, main language spoken at home, parental support for schoolwork, and classroom glazing type. Further analyses were then conducted, additionally adjusting model 2 for acute noise exposure during testing, dyslexia, hearing impairment, noise annoyance, episodic memory (recognition, conceptual recall, and information recall), working memory, and sustained attention. Hearing impairment was defined as suffering recurrent (earache, ear infection, glue ear, temporary hearing loss) or serious hearing problems (adenoids removed, grommets fitted, long-term hearing loss, hearing aid). Models 1 and 2 were additionally run by substituting aircraft noise exposure at home for aircraft noise exposure at school. To examine combined-exposure effects for aircraft noise, model 2 was additionally adjusted for aircraft noise exposure at school and home, using a measure whereby home aircraft noise exposure for each pupil was centered at his or her school aircraft noise exposure (school noise subtracted from home noise) to assess the effect of the difference between a pupil's home aircraft noise exposure and his or her exposure at school.

The possibility of a curvilinear exposure-effect relation between noise (either aircraft or road traffic) and reading comprehension was investigated by using fractional polynomial models (25✦). The best-fitting model from a set of two-degree fractional polynomials (of the form $ß_1$aircraft noise$^{p1}$ + $ß_2$noise$^{p2}$, where $p_1$ and $p_2$ belong to the set –2, –1, –0.5, 0, 0.5, 1, 2, 3) was chosen; then, the goodness of fit (deviance) of this model was compared with the goodness of fit of a straight-line model to test for departure from a straight-line relation.

## RESULTS

**Descriptive results**
Table 1 illustrates the characteristics of the overall RANCH sample. Participants were 2,844 children aged 9–10 years (Netherlands = 762, Spain = 908, United Kingdom = 1,174) from 89 schools (Netherlands = 33, Spain = 27, United Kingdom = 29). The average age was 10 years, 6 months; 53 percent were female. The overall child response rate was 89 percent and for the parent questionnaire was 80 percent. Participation rates did not vary significantly across noise exposure categories. Completed parent questionnaires were available for 2,276 (80 percent) of the children who participated. There were sociodemographic differences between the countries in terms of parental employment status, home ownership, crowding in the home, and main language spoken at home. These findings reflect sociodemographic differences between the countries and were adjusted for in the analyses. Aircraft noise exposure ranged from 30 to 77 dB(A); mean aircraft noise exposure was lower in Spain than in the United Kingdom or the Netherlands (table 1). Road traffic noise exposure ranged from 32 to 71 dB(A) and was similar across the three countries.

Subjects for whom no values for the potential confounders outlined in table 1 were missing were included in the analysis. The subsample consisted of 88 percent of the overall sample (total $N$ = 2,010; Netherlands = 583, Spain = 572, United Kingdom = 855) and did not differ significantly from the overall sample in terms of sociodemographic characteristics or in terms of reading and cognitive test scores (table 2).

**TABLE 2. Mean, standard deviation, and range for the reading comprehension, episodic memory, working memory, sustained attention, and annoyance tasks for the RANCH sample, overall and by country, the RANCH project, 2001–2003**

| Outcome | Pooled sample ($n$ = 2,844) | United Kingdom ($n$ = 1,174) | The Netherlands ($n$ = 762) | Spain ($n$ = 908) |
|---|---|---|---|---|
| Reading comprehension | | | | |
| *z* score | | | | |
| Mean (SD*) | 0.00 (1.00) | 0.00 (1.00) | 0.00 (1.00) | 0.00 (1.00) |
| Range | –2.36 to 3.07 | –2.09 to 2.55 | –2.05 to 2.31 | –2.36 to 3.07 |
| Original score | | | | |
| Mean (SD) | | 51.62 (11.76) | 23.12 (7.49) | 11.62 (4.32) |
| Range | | 6 to 79 | 7 to 41 | 1 to 25 |
| Recognition memory | | | | |
| Mean (SD) | 25.08 (2.46) | 24.94 (2.64) | 25.35 (2.03) | 25.04 |

| | | | | |
|---|---|---|---|---|
| | | | | (2.51) |
| Range | 13 to 30 | 14 to 30 | 18 to 30 | 13 to 30 |
| Information recall | | | | |
| Mean (SD) | 17.68 (5.24) | 18.60 (5.42) | 16.71 (4.54) | 17.33 (5.35) |
| Range | 0 to 30.5 | 0 to 30.5 | 1 to 28 | 0 to 30.5 |
| Conceptual recall | | | | |
| Mean (SD) | 4.86 (1.40) | 5.18 (1.41) | 4.98 (1.27) | 4.37 (1.36) |
| Range | 0 to 9 | 0 to 9 | 0.5 to 8 | 0 to 7 |
| Working memory | | | | |
| Mean (SD) | 16.16 (7.28) | 14.82 (7.39) | 16.73 (7.06) | 17.32 (7.06) |
| Range | –13 to 35 | –13 to 32 | –10 to 33 | –13 to 35 |
| Sustained attention | | | | |
| Mean (SD) | 101.72 (42.94) | 94.96 (44.52) | 102.68 (41.80) | 109.57 (40.33) |
| Range | –97 to 222 | –97 to 220 | –95 to 205 | –92 to 222 |
| Aircraft noise annoyance at school† | | | | |
| Mean (SD) | 2.01 (1.02) | 2.17 (1.08) | 1.96 (0.93) | 1.82 (0.98) |
| Range | 1 to 5 | 1 to 5 | 1 to 5 | 1 to 5 |

**Effects of aircraft noise at school on reading comprehension**
Increasing aircraft noise exposure at school was significantly related to poorer reading comprehension ($\chi^2 = 6.62$, df = 1, $p = 0.012$; table 3). In the adjusted model, as noise increased by 5 dB(A), performance on the reading test (measured by *z* scores) decreased by –0.040 marks for the overall sample. Children scored lower on the reading test if they had a mother with low educational attainment or if they had a long-standing illness; they scored higher if their parents were homeowners, if the children spoke the main language of the country, and if they perceived a high level of parental support for schoolwork. The effect of aircraft noise exposure on reading comprehension remained when the model was further adjusted for dyslexia, hearing impairment, and acute noise during testing, as well as for working memory, sustained attention, and episodic memory (conceptual recall and information recall) (table 4); the significance of the effect was borderline after adjustment for recognition memory ($p = 0.062$) and aircraft noise annoyance ($p = 0.05$).

**TABLE 3. Multilevel model parameter estimates for aircraft noise and road traffic noise and reading comprehension for the pooled data, the RANCH project, 2001–2003**

| | Model (*N* = 2,010) | | |
|---|---|---|---|
| | Aircraft noise at | Road traffic noise at | Aircraft noise at |

| | school, unadjusted | | | school, unadjusted | | | school and road traffic noise at school, adjusted* | | |
|---|---|---|---|---|---|---|---|---|---|
| | ß | SE† | *p* value | ß | SE | *p* value | ß | SE | *p* value |
| Fixed coefficients | | | | | | | | | |
| Intercept | 0.404 | 0.167 | | –0.168 | 0.223 | | –1.364 | 0.625 | 0.02 |
| Aircraft noise at school | –0.007 | 0.003 | 0.013 | | | | –0.008 | 0.003 | 0.012 |
| Road traffic noise at school | | | | 0.003 | 0.004 | 0.454 | 0.002 | 0.004 | 0.54 |
| Spain | | | | | | | 1.00 | | |
| United Kingdom | | | | | | | 0.272 | 0.082 | 0.001 |
| The Netherlands | | | | | | | 0.320 | 0.084 | <0.001 |
| Age | | | | | | | 0.162 | 0.147 | 0.271 |
| Female gender | | | | | | | –0.056 | 0.042 | 0.18 |
| Parents employed | | | | | | | 0.080 | 0.064 | 0.21 |
| Crowding at home | | | | | | | –0.073 | 0.054 | 0.18 |
| Parents' home ownership | | | | | | | 0.205 | 0.053 | <0.001 |
| Mother's education | | | | | | | –0.713 | 0.077 | <0.001 |
| Long-standing illness | | | | | | | –0.147 | 0.004 | 0.003 |
| Main language spoken at home | | | | | | | 0.183 | 0.076 | 0.016 |
| Parental support | | | | | | | 0.084 | 0.011 | <0.001 |
| Classroom glazing | | | | | | | 0.001 | 0.027 | 0.95 |
| Random parameters | | | | | | | | | |
| Level 2: school | 0.042 | 0.013 | | 0.049 | 0.014 | | 0.023 | 0.010 | |
| Level 1: pupil | 0.951 | 0.030 | | 0.950 | 0.030 | | 0.865 | 0.279 | |

* The adjusted models were evaluated against a model with the noise source excluded. Aircraft noise adjusted $\chi^2$ = 6.62, df = 1, $p$ = 0.012; road traffic noise adjusted $\chi^2$ = 0.37, df = 1, $p$ = 0.54.

SE, standard error.

**TABLE 4. Multilevel model parameter estimates for aircraft noise at school on reading comprehension, additionally adjusted for memory outcomes and aircraft noise annoyance, the RANCH project, 2001–2003**

| | No. | Aircraft noise at school, adjusted | | |
|---|---|---|---|---|
| | | ß | SE* | $p$ value |
| Adjusted† | 2,010 | –0.008 | 0.003 | 0.012 |
| Adjusted† + working memory | 1,920 | –0.006 | 0.002 | 0.015 |
| Adjusted† + recognition memory | 1,978 | –0.005 | 0.002 | 0.062 |
| Adjusted† + conceptual recall | 1,953 | –0.006 | 0.002 | 0.018 |
| Adjusted† + information recall | 1,952 | –0.006 | 0.002 | 0.028 |
| Adjusted† + sustained attention | 1,918 | –0.008 | 0.002 | 0.003 |
| Adjusted† + aircraft noise annoyance | 1,926 | –0.006 | 0.003 | 0.05 |

* SE, standard error.

† Adjusted for age, gender, country, mother's education, employment status, crowding at home, home ownership, long-standing illness, main language spoken at home, parental support, classroom glazing, and road traffic noise exposure

In all three countries, the same inverse relation between aircraft noise exposure at school and reading comprehension was found (table 5, test of heterogeneity $p$ = 0.9). In the Netherlands and Spain, a 20-dB(A) increase in aircraft noise was associated with a decrement of one eighth of a standard deviation on the reading test; in the United Kingdom, the decrement was one fifth of a standard deviation. The size of the effect did not differ for high and low socioeconomic position. In terms of reading age, when the national data relating to the reading comprehension tests were used (16, 17), one eighth of a standard deviation was equivalent to an 8-month difference in reading age in the United Kingdom and a 4-month difference in reading age in the Netherlands. No comparative national data were available for the Spanish ECL-2 test (18).

**TABLE 5. Effect size of aircraft noise and road traffic noise on reading comprehension for the pooled data and for each country, the RANCH project, 2001–2003**

| | ß | SE* | 95% CI* | $p$ value from $\chi^2$† |
|---|---|---|---|---|
| Aircraft noise at school | | | | |

| | | | | |
|---|---|---|---|---|
| Pooled estimate‡ | –0.008 | 0.003 | –0.014, –0.002 | 0.012 |
| United Kingdom§ | –0.009 | 0.005 | –0.019, 0.001 | |
| The Netherlands§ | –0.006 | 0.007 | –0.020, 0.008 | |
| Spain§ | –0.006 | 0.005 | –0.016, 0.004 | |
| Road traffic noise at school | | | | |
| Pooled estimate‡ | 0.002 | 0.004 | –0.005, 0.009 | 0.54 |
| United Kingdom§ | –0.003 | 0.006 | –0.014, 0.009 | |
| The Netherlands§ | 0.004 | 0.005 | –0.007, 0.014 | |
| Spain§ | 0.008 | 0.008 | –0.009, 0.024 | |

[*] SE, standard error; CI, confidence interval.

[†] Test of heterogeneity: aircraft noise $p = 0.9$, road traffic noise $p = 0.10$.

[‡] Adjusted for age, gender, country, mother's education, employment status, crowding, home ownership, long-standing illness, main language spoken at home, parental support, classroom glazing, and road traffic noise exposure.

[§] Adjusted for all factors except country given in the previous footnote

Figure 1 shows reading comprehension adjusted for age, gender, and country by 5-dB(A) bands of aircraft noise. There was no significant departure from linearity when we compared straight-line fit with best-fitting fractional polynomial curve ($p = 0.99$).

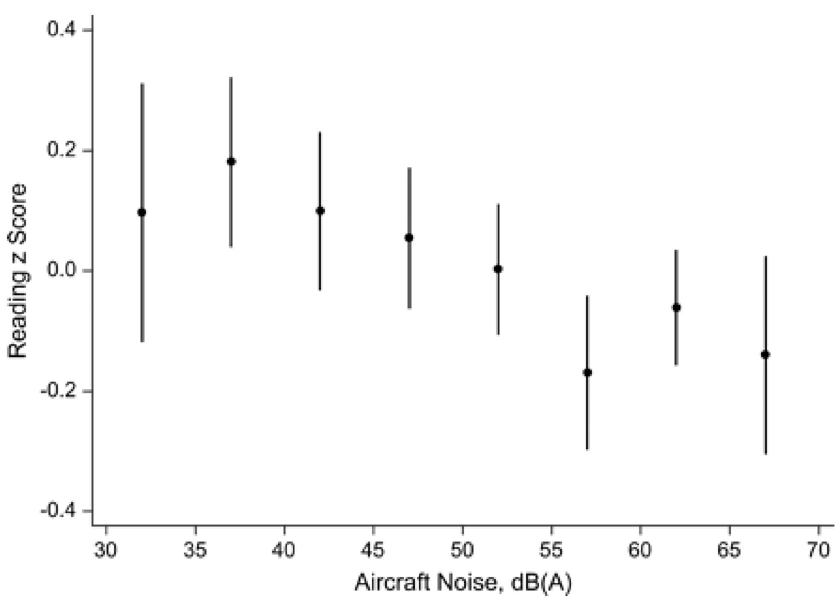


**FIGURE 1.** Adjusted mean reading *z* scores and 95% confidence intervals for 5-dB(A) bands of aircraft noise at school (adjusted for age, gender, and country), the RANCH project, 2001–2003. dB(A), a measure of sound level in decibels A-weighted to approximate the typical sensitivity of the human ear.

**Effects of aircraft noise exposure at home on reading comprehension**

Aircraft noise exposure at home was highly correlated with aircraft noise exposure at school (Netherlands: $r = 0.93$, Spain: $r = 0.85$, United Kingdom: $r = 0.91$) (figure 2). Increasing aircraft noise exposure at home was significantly and linearly related to poorer reading comprehension ($\chi^2 = 5.88$, df =1, $p = 0.015$). There was no additional effect of home aircraft noise exposure after adjustment for aircraft noise exposure at school ($\chi^2 = 0.24$, df = 1, $p = 0.625$) (table 6).

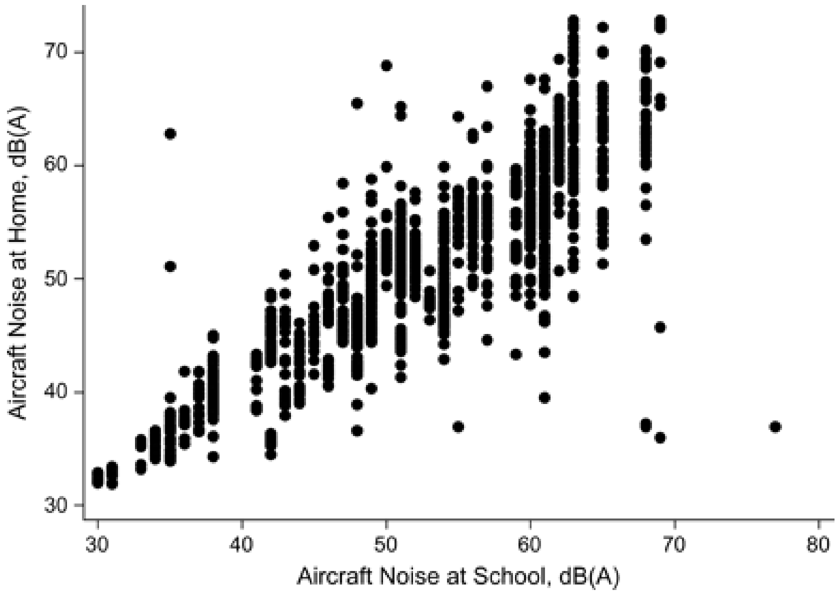


**FIGURE 2.** Association between aircraft noise exposure at school and aircraft noise exposure at home for the pooled data from the RANCH project, 2001–2003. dB(A), a measure of sound level in decibels A-weighted to approximate the typical sensitivity of the human ear.

**TABLE 6. Multilevel model parameter estimates for aircraft noise at home and school and road traffic noise at school on reading comprehension for the pooled data***

| | Model | | | | | |
|---|---|---|---|---|---|---|
| | Aircraft noise at home and road traffic noise at school, adjusted† | | | Aircraft noise at home and school, and road traffic noise at school, adjusted | | |
| | ß | SE‡ | *p* value | ß | SE | *p* value |
| Aircraft noise at home | –0.008 | 0.003 | 0.015 | –0.003 | 0.006 | 0.6 |
| Aircraft noise at school | | | | –0.009 | 0.003 | 0.008 |
| Road traffic noise at school | 0.002 | 0.004 | 0.50 | 0.002 | 0.004 | 0.5 |

[*] The adjusted models were evaluated against a model with the noise source excluded. Aircraft noise at home adjusted $\chi^2 = 5.88$, df = 1, $p = 0.015$; aircraft noise at home and school adjusted $\chi^2 = 0.24$, df = 1, $p = 0.625$.

[†] Both models were additionally adjusted for country, age, gender, mother's education, employment status, crowding, home ownership, long-standing illness, main language spoken at home, parental support, and classroom glazing.

[‡] SE, standard error

**Effects of road traffic noise at school on reading comprehension**
Chronic road traffic noise exposure at school had no significant effect on reading comprehension either before ($\chi^2 = 0.44$, df = 1, $p = 0.51$; model not shown) or after ($\chi^2 = 0.37$, df = 1, $p = 0.54$; table 3) adjustment for aircraft noise exposure at school. In addition, there was no significant departure from linearity for reading comprehension adjusted for age, gender, and country ($p = 0.90$ for comparison of straight-line fit with best-fitting fractional polynomial curve).

## DISCUSSION

The aim of this study was to compare performance on a standardized reading comprehension task for children aged 9–10 years attending schools exposed to varying levels of aircraft noise and road traffic noise around major airports in three European countries. There were three main findings. Firstly, a linear exposure-effect relation was found between aircraft noise exposure at school and impaired reading comprehension, with a similar effect being observed in all three countries. Secondly, the effect of aircraft noise on reading comprehension could not be accounted for by sociodemographic variables, acute noise during testing, aircraft noise annoyance, episodic memory, working memory, or sustained attention. Thirdly, there was no evidence of a relation between road traffic noise at school and reading comprehension. These results raise concerns regarding the effect of chronic aircraft noise exposure on children's reading ability.

This is the first study known to establish that the exposure-effect relation between aircraft noise and reading comprehension is linear. In all three countries, a negative relation was found between aircraft noise exposure at school and reading comprehension. These results are consistent with previous studies (1, 3) but less consistent with the West London Schools and the Munich studies, which reported an effect for only the most difficult items on a standardized reading test (10, 12). The current study utilized an exposure-effect measure of aircraft noise exposure, examining a wider range of noise exposures, while the previous studies categorized children into low and high aircraft noise exposure, thus limiting the power of the studies.

The magnitude of the effect of aircraft noise on reading comprehension did not differ among countries. In the Netherlands and Spain, a 20-dB(A) increase in aircraft noise was associated with a decrement of one eighth of a standard deviation on the reading test; in the United Kingdom, the decrement was one fifth of a standard deviation. Although the magnitude of the effect of aircraft noise on reading is small, the consequences of long-term exposure on reading comprehension remain unknown. It is possible that children could be exposed to aircraft noise for many of their childhood years; in the United Kingdom and Spain, high environmental noise exposure is often found in socially deprived areas, where social mobility is low. While the Munich study (12) demonstrated that the effects of aircraft noise exposure on reading comprehension are reversible if the noise ceases, studies have yet to examine the long-term developmental consequences of exposure that persists throughout a child's education. Demand for air travel continues to increase, and further knowledge about cumulative exposure would inform intervention strategies and policy decisions.

In some previous studies, the association between noise exposure and reading has been confounded by socioeconomic status (10). Our study examined a comprehensive set of individual-level socioeconomic status variables in all three countries and found that the relation between aircraft noise exposure and reading comprehension could not be accounted for by socioeconomic status or other individual-level factors, such as long-standing illness and parental support for schoolwork. The United Kingdom sample, despite being of lower socioeconomic status, responded to noise exposure similarly to the more affluent Dutch and Spanish samples, suggesting that socioeconomic factors do not explain the effect of aircraft noise on reading.

The relation between aircraft noise exposure and reading comprehension was not mediated by sustained attention, working memory, or episodic memory: the significance of the effect was borderline after adjustment for the recognition measure of episodic memory but remained after adjustment for conceptual recall and information recall. There was limited support for a finding that the relation was not mediated by noise annoyance (1). These results, together with previous findings (1, 12), suggest that noise may either directly affect reading comprehension or be accounted for by other mechanisms. It is postulated that noise restricts attention to central cues during complex language-related tasks (4, 26, 27). The current research has not examined the psycholinguistic mechanisms that may underlie the effect, and further research on psycholinguistic mechanisms will inform the design of educational and environmental interventions for children in schools exposed to high levels of aircraft noise.

Aircraft noise exposure at school and home independently demonstrated a comparable association with reading comprehension. There was substantial colinearity between school and home aircraft noise exposure, which has been demonstrated previously (10), making it difficult to assess whether exposure at school or home differentially affected reading comprehension. After centering home aircraft noise exposure on school aircraft noise exposure (subtracting school exposure from home exposure), we demonstrated that there was no additional effect of home aircraft noise exposure after adjustment for aircraft noise exposure at school. It was not possible to fully establish the relative contribution of home and school exposure over a full 24-hour period to cognitive deficits in children in this study, and this is an important challenge for future research.

We found no significant effect of road traffic noise exposure on reading comprehension, which refuted our hypothesis and is inconsistent with previous studies (4, 5). However, the levels of road traffic noise in this study were not as high as those in some previous studies. In the Cohen et al. study (4), noise levels were typically above 80 dB(A) based on the mode of 5-minute measures at home. In this study, the annual equivalent levels ranged from 32 to 71 dB(A) at school. It is also possible that exposure to road traffic noise at home may influence reading either in its own right or by interacting with exposure at school. Unfortunately, national data on road traffic noise exposure at home were not available. No definite conclusion about the effect of road traffic noise exposure can be drawn until the results of the current study are replicated and the effect of home road traffic noise exposure is investigated.

Why should there be an effect for aircraft but not road traffic noise? Aircraft noise is more intense and less predictable than road traffic noise. The transient nature of aircraft flyovers, which have high short-term noise levels, may disrupt children's concentration and distract them from learning tasks, while the constant nature of road traffic noise may allow children to habituate and not be distracted. Banbury et al. (28) suggest that sound that varies appreciably over time will impair cognitive performance, whereas sound that does not is associated with little or no impairment. Aircraft noise exposure may also cause higher arousal levels than road traffic noise, and high arousal will interfere with performance tasks such as reading comprehension (29). A further explanation for the lack of an effect for road traffic noise exposure is that differences between countries in estimating road traffic noise exposure may have resulted in a differential quality in exposure assessment. Traffic flow may have been underestimated; exposure misclassification may also have occurred because classrooms were at varying distances from the façade of the school building.

Our study has limitations: reading measures not being exactly equivalent across countries, reliance on external measures of noise exposure, and lack of data about noise exposure over the 24 hours. However, this study represents an improvement on previous studies because of its size, in terms of both number of participants and schools. To our knowledge, it is the largest study of noise exposure and cognition in children and is the only study able to compare the reading effect size in different countries across a wide range of noise exposures. Application of multilevel modeling enabled the effect of both school-level and individual-level variables to be examined. A further strength of the study is the comprehensive number of individual-level socioeconomic variables that were examined.

In conclusion, our results suggest that aircraft noise exposure is linearly associated with impaired reading comprehension. No association was found between road traffic noise exposure and reading comprehension, either in the absence or the presence of aircraft noise. However, we could not rule out an effect at higher levels of road traffic noise. The consistent findings across the three countries, with substantial differences regarding a range of socioeconomic and environmental variables, offer robust evidence of an exposure-effect relation between aircraft noise and reading comprehension.

**ACKNOWLEDGMENTS**

The RANCH project was funded by the European Community (QLRT-2000-00197) in the Vth framework programme under Key Action 1999:/C 361/06 "Quality of life and management of living resources." The RANCH project was co-funded by the Department of Environment, Food and Rural Affairs (United Kingdom); the Dutch Ministry of Public Health, Welfare and Sports; the Dutch Ministry of Spatial Planning, Housing and the Environment; and the Dutch Ministry of Transport, Public Works and Water Management (the Netherlands).

Ethical approval was provided by the East London and the City Local Research Ethics Committee, East Berkshire Local Research Ethics Committee, Hillingdon Local Research Ethics Committee, and the Hounslow District Research Ethics Committee in the United Kingdom; by the Medical Ethics Committee of TNO, Leiden in the Netherlands; and by the CSIC Bioethical Commission, Madrid in Spain.

The authors thank all pupils, parents, and teachers who participated and the other members of the RANCH team: Eldar Aarsten, Rebecca Asker, Östen Axelsson, Birgitta Berglund, Bernard Berry, Sarah Brentnall, Rachel Cameron, Paul Fischer, Anita Gidlöf Gunnarsson, Emina Hadzibajramovic, Maria Holmes, Staffan Hygge, Mats E. Nilsson, E. Öhrström, Britth Sandin, Rebecca Stellato, Helena Svensson, and Irene van Kamp.

Conflict of interest: none declared.

## REFERENCES

1. Haines MM, Stansfeld SA, Job RF, et al. Chronic aircraft noise exposure, stress responses, mental health and cognitive performance in school children. Psychol Med 2001;31:265–77.

2. Evans GW, Hygge S, Bullinger M. Chronic noise and psychological stress. Psychol Sci 1995;6:333–8.

3. Evans GW, Maxwell L. Chronic noise exposure and reading deficits: the mediating effect of language acquisition. Environ Behav 1997;29:638–56.

4. Cohen S, Glass DC, Singer JE. Apartment noise, auditory discrimination, and reading ability in children. J Exp Soc Psychol 1973;9:407–22.

5. Lukas JS, DuPree RB, Swing JW. Report of a study on the effects of freeway noise on academic achievement of elementary school children. Sacramento, CA: California Department of Health Services, 1981.

6. Shield B, Dockrell J. The effects of noise on the attainments and cognitive performance of primary school children. Department of Health, United Kingdom, 2002. (http://www.dh.gov.uk/PolicyAndGuidance/HealthAndSocialCareTopics/NoisePollution/Nois

ePollutionGeneralInformation/NoisePollutionGeneralArticle/fs/en?CONTENT_ID=4031962&chk=9Pe4Jx).

7. Stansfeld SA, Berglund B, Clark C, et al. Aircraft and road traffic noise and children's cognition and health: exposure-effect relationships. Lancet 2005;365:1942–9.

8. Haines MM, Stansfeld SA, Head J, et al. Multilevel modelling of aircraft noise on performance tests in schools around Heathrow Airport London. J Epidemiol Community Health 2002;56:139–44.

9. Green KB, Pasternack BS, Shore RE. Effects of aircraft noise on reading ability of school-age children. Arch Environ Health 1982;37:24–31.

10. Haines MM, Stansfeld SA, Brentnall S, et al. The West London Schools Study: the effects of chronic aircraft noise exposure on child health. Psychol Med 2001;31:1385–96.

11. Haines MM, Stansfeld SA, Job RF, et al. A follow-up study of effects of chronic aircraft noise exposure on child stress responses and cognition. Int J Epidemiol 2001;30:839–45.

12. Hygge S, Evans GW, Bullinger M. A prospective study of some effects of aircraft noise on cognitive performance in school children. Psychol Sci 2002;13:469–74.

13. Bronzaft AL. The effect of a noise abatement program on reading ability. J Environ Psychol 1981;1:215–22.

14. Cohen S, Evans GW, Stokols D, et al. Behavior, health and environmental stress. New York, NY: Plenum Press, 1986.

15. Dassen AG, Jabben J, Dolmans JHJ. Development and use of EMPARA: a model for analysing the extent and effects of local environmental problems in the Netherlands. The Hague, the Netherlands: proceedings of the 2001 International Congress and Exhibition on Noise Control Engineering, 2001.

16. Hagley F. Suffolk reading scale 2. Windsor, United Kingdom: NFER-NELSON, 2002.

17. Staphorsius G. Readability and reading proficiency. The development of a domain–related instrument. (In Dutch). Arnhem, the Netherlands: CITO, 1994.

18. De La Cruz.V. Evaluación Comprensión Lectora. ECL-2. Madrid, Spain: TEA Ediciones, SA, 1999.

19. Mackenbach JP, Kunst AE. Measuring the magnitude of socio-economic inequalities in health: an overview of available measures illustrated with two examples from Europe. Soc Sci Med 1997;44:757–71.

20. Cohen MJ. Children's Memory Scale manual. San Antonio, TX: The Psychological Corporation Harcourt Brace & Company, 1997.

21. Toulouse E, Pieron H. Test of perception and attention. (In Spanish). Madrid, Spain: TEA Ediciones, SA, 1986.

22. Smith AP, Miles C. The combined effects of occupational health hazards: an experimental investigation of the effects of noise, nightwork and meals. Int Arch Occup Environ Health 1987;59:83–9.

23. Hygge S, Boman E, Enmarker I. The effects of road traffic noise and meaningful irrelevant speech on different memory systems. Scand J Psychol 2003;44:13–21.

24. Rasbash J, Brown W, Goldstein H, et al. A user's guide to MLwiN. London, United Kingdom: Centre for Multilevel Modelling, Institute of Education, University of London, 2002.

25. Royston P, Altman DG. Regression using fractional polynomials of continuous covariates: parsimonious parametric modelling. Appl Stat 1994;43:429–67.

26. Cohen S, Evans GW, Krantz DS, et al. Physiological, motivational, and cognitive effects of aircraft noise on children. Am Psychol 1980;35:231–43.

27. Evans GW, Lepore SJ. Non-auditory effects of noise on children. Child Environ 1993;10:31–51.

28. Banbury SP, Macken WJ, Tremblay S, et al. Auditory distraction and short-term memory: phenomena and practical implications. Hum Factors 2001;43:12–29.

29. Yerkes RM, Dodson JD. The relation of strength of stimulus to rapidity of habit formation. J Comp Neurol Psychol 1908;18:459–82.